GRAH-RA
73-1247

# Lithium niobate stress gauge for pulsed radiation deposition studies*

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(Received 10 September 1973)

The piezoelectric response of impact-loaded $z$-cut lithium niobate is investigated to determine whether the material can be used as a time-resolving nanosecond-resolution stress gauge. The material is found to have appropriate properties for stresses up to 15 kbar. A gauge from this material should prove particularly useful for measurements of stress pulses resulting from the absorption of pulsed radiation in solids.

When a sample is subjected to an intense short-duration (~$10^{-8}$ sec) radiation source, such as a pulsed electron beam or a pulsed high-power laser, a stress pulse is produced in the sample due to absorption of the energy under approximately constant volume conditions.[1,2] A quantitative time-resolved measurement of the stress pulse provides a sensitive probe of inherent thermomechanical interactions on the time scale of the deposition.[3,4] Measurement of such stress pulses are typically accomplished with the Sandia quartz gauge[5] which utilizes the piezoelectric effect to produce a short-circuited current that is proportional to stress, or with optical interferometric techniques[6] which measure displacement[7] or velocity[8,9] as a function of time. All these techniques provide the capability of detecting changes in stress or velocity with a time resolution of a few nanoseconds.

Various investigators have used stress pulse measurements to determine Grüneisen constants of solids[10–14] and composite materials,[15,16] to determine effects of surface blowoff,[17,18] to relate mechanical damage to stress,[19–21] and as a calorimeter to monitor the deposition.[4] One investigator has demonstrated subnanosecond rise times of stress pulses produced by 2–3-psec laser pulses.[17]

One of the principal limitations for stress pulse measurements with the quartz gauge has been the small irradiation area often employed to impart higher energy densities in samples. Since the signal level from the gauge is directly proportional to the area of the gauge, small areas lead to small signal levels which may provide inadequate signal-to-noise ratios. The object of the present paper is to report on the feasibility of utilizing a new piezoelectric gauge whose active element is $z$-cut lithium niobate. Since $z$-cut lithium niobate has an order-of-magnitude larger longitudinal piezoelectric stress constant than $x$-cut quartz,[22] the new gauge will provide a larger signal or permit smaller gauge sizes for stress measurements of intense pulsed irradiation experiments.

In a linear approximation[23] it can be shown that[5] any one-dimensional piezoelectric disk produces a short-circuited current $i(t)$, which is a time-resolved replica of the stress at the input electrode, $\sigma(t)$. The stress and current are related by the equation

$$\sigma(t)=(t_0/kA)i(t), \quad 0<t<t_0, \ldots \qquad (1)$$

where $t_0$ is the transit time of an elastic wave through the thickness $l$, $k$ is a mildly stress-dependent coefficient relating piezoelectric current to stress in uniaxial strain [in the zero stress limit $k=e_{xx}(C^E_{xx})^{-1}$, where $x$ is the propagation direction and $C^E$ is the constant electric field elastic constant], and $A$ is the area of the charge-collecting electrode. Since the polarization signal is coupled to the electrode with the speed of an electromagnetic wave in the piezoelectric solid, the

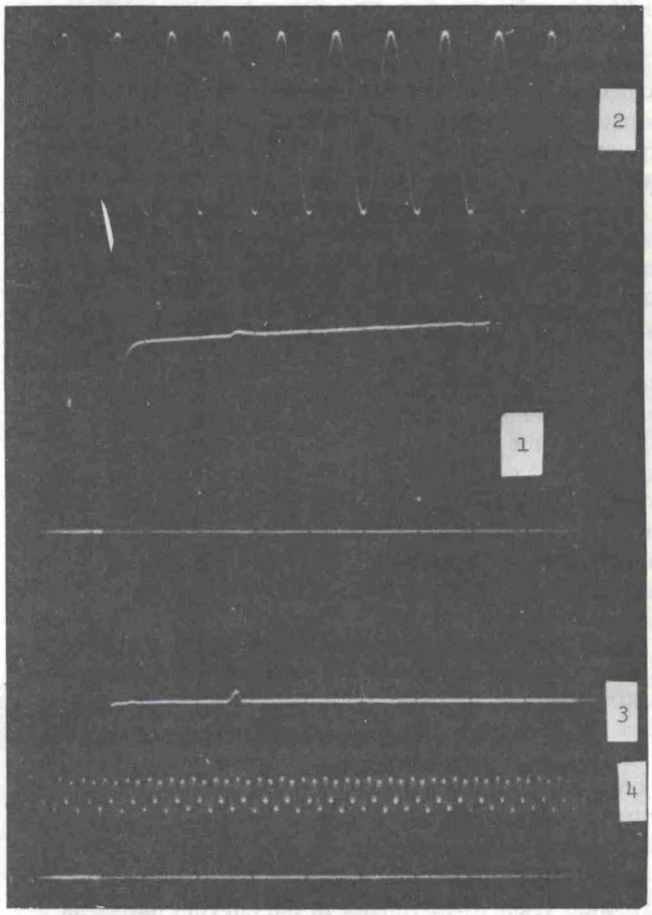

FIG. 1. Current-time response for $z$-cut lithium niobate impact loaded at 12 kbar. Traces 2 and 3 are low-frequency and pulse voltage calibrations, respectively. Trace 4 is a 100-MHz timing wave. The data trace in the center proceeds from left to right. Following a horizontal trace immediately prior to impact, the current jumps to some initial value in a time which is too short to adequately show on the record. The current then shows a small increase in time as the shock propagates through the sample, then shows a sharp drop when the shock wave reaches the rear electrode. The duration of the pulse from the sample is 360 nsec. The amplitude of the signal is about 2 A.

recorded signal is limited only by the rise time of the signal transmission and recording equipment and the planarity of the stress pulse over the area $A$.

Although any piezoelectric material may, in principle, be used as the active gauge element, a typical experiment destroys the gauge such that the gauge is not subject to calibration under the conditions of use. Hence, a material with known reproducible physical properties must be employed. The requirement for reproducibility of the present gauges is more difficult to obtain than for conventional transducers, since typical stresses are tens of kilobars and electric fields are typically $10^5$ V $\mathrm{cm}^{-1}$. Previously, $x$-cut quartz was the only material available with suitable properties. To determine whether $z$-cut lithium niobate, which has recently become commercially available in suitable quality and size, has suitable properties, an experimental program has been accomplished to study the material under well-controlled impact loading. The material investigated was "transducer grade" lithium niobate obtained from Crystal Technology, Inc.

The experimental technique is similar to that employed for previous investigations of piezoelectric response. Previous publications may be consulted for experimental detail.[24,25] Disks of $z$-cut lithium niobate constructed in a guard-ring configuration are subjected to direct precisely controlled impacts with $x$-cut quartz disks. The velocity of the impacting disk and the current-time response of the sample are measured on each experiment. The duration of the current pulse through known sample thicknesses provides a measure of the shock-wave velocity. The measured impact velocity is used to determine the particle velocity imparted to the disk. The resulting strain and stress can then be computed from the conservation of mass and momentum. Experiments were conducted at impact velocities ranging from 0.02 to 0.32 mm $\mu\mathrm{sec}^{-1}$, corresponding to stresses of from 2 to 34 kbar. The maximum experimental error of the gauge output coefficient is estimated to be ± 1.5%.

A typical current-time pulse obtained for a stress of 12 kbar is shown in Fig. 1. Upper and lower traces are calibration traces. In the data trace time increases from left to right. The oscilloscope is triggered prior to impact such that the horizontal trace at the beginning of the record corresponds to conditions immediately prior to impact. The impact produces a sharp rise in current over a time interval equal to the time interval to impact the entire area of the sample. The nearly horizontal trace after impact is the current output as the shock wave traverses the disk. The current then drops sharply when the elastic shock wave reaches the rear electrode. The small increase in current during wave transit time is due principally to electromechanical coupling effects which are not taken into account by Eq. (1). Appropriate values for $k$ are determined from measured values of the jump in current at $t = 0+$ and stress values are computed from the measured projectile velocity. Values for the $k$ coefficient [see Eq. (1)] are plotted in Fig. 2. It can be seen that $k$ shows a mild increase with stress. The data are fitted by the relation $k = (7.33 \pm 0.054) \times 10^{-8}$ C $\mathrm{cm}^{-2}\mathrm{kbar}^{-1} + (0.023 \pm 0.0055)\sigma \times 10^{-8}$ C $\mathrm{cm}^{-2}\mathrm{kbar}^{-2}$, where the ± indicates standard errors. A measured wave velocity of 7.33 mm $\mu\mathrm{sec}^{-1}$ was used to compute the values for $k$.

Application of Eq. (1) requires that stresses be less than the Hugoniot elastic limit and that shock-induced conductivity be absent. The Hugoniot elastic limit was determined in a "front-back" quartz gauge impact experiment.[26] For an input stress of 40 kbar the measured elastic wave, after a propagation distance of 2.6 mm, was found to have a peak amplitude of 24.5 kbar, with a relaxation to a lower stress of 19.0 kbar in about 150 nsec. Shock-induced conductivity is observed in electrical response measurements above 15 kbar; thus, our measurements indicate that $z$-cut lithium niobate has suitable properties for the active element of a time-resolving piezoelectric stress gauge for stresses up to 15 kbar.

The larger piezoelectric stress constant of lithium niobate compared to quartz leads to a signal gain over a quartz gauge at the same input stress. Because of the different acoustic impedances between quartz and lithium niobate, the actual signal gain depends on the acoustic impedance of the sample material. Signal levels for stress pulses transmitted into lithium niobate and quartz are compared for samples of a wide range of acoustic impedances in Table I. It can be observed that currents from 5—9 times greater than quartz will be generated.

Although it remains to be demonstrated whether $z$-cut lithium niobate exhibits the negative-polarity anomaly[27] or the short-pulse anomaly[28] characteristic of shock-induced conductivity in $x$-cut quartz, the present work indicates that the material has suitable properties and exhibits the excellent reproducibility required for stress pulse measurements. This capability has been demonstrated by measurement of a radiation-induced stress pulse in an aluminum target subjected to the 50-nsec duration electron beam from the Nereus[29] pulsed electron beam machine. The gauge performed as anticipated from the impact studies reported in the present paper.

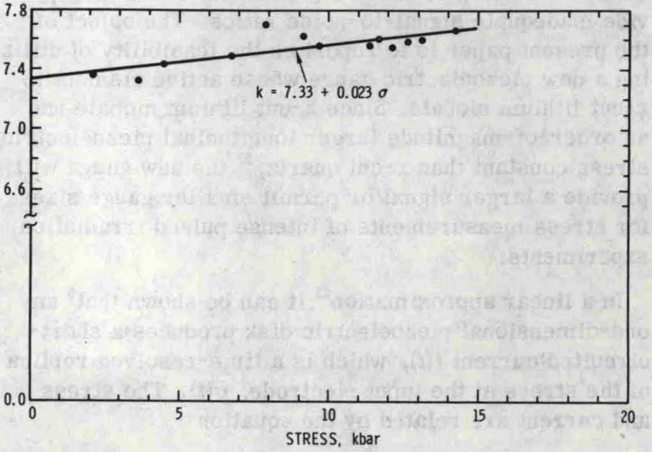

FIG. 2. Piezoelectric current coefficient $k$ at various elastic impact stresses. The coefficient is found to exhibit a small increase with stress. At stresses greater than 15 kbar, shock-induced conductivity prohibits use of $z$-cut lithium niobate as a gauge.

TABLE I. Output signals for $z$-cut lithium niobate gauges relative to quartz gauges.

| Sample | $\rho_0 c$ [a] (g cm$^{-2}$ $\mu$sec$^{-1}$) | $i_L/i_Q$ [b] |
|---|---|---|
| PMM$_A$ [c] | 0.35 | 5.2 |
| 6061-T6 aluminum | 1.74 | 6.7 |
| Mild steel | 4.67 | 8.3 |
| Tungsten | 10.0 | 9.1 |

[a] Nominal acoustic impedance values are shown for illustrative purposes. $\rho_0$ is the density and $c$ is the dilatational wave velocity.

[b] $i_L$ and $i_Q$ are currents from $z$-cut lithium niobate and $x$-cut quartz, respectively, for common gauge dimensions and common stress in the sample. The ratio is calculated in the low-stress limit utilizing the linear acoustic mismatch $\sigma_g = 2Z_g(Z_g + Z_s)^{-1}\sigma_s$, where $\sigma_g$ and $\sigma_s$ are the stress in the gauge and the incident stress in the sample, respectively. Similarly, $Z_g$ and $Z_s$ are acoustic impedances, $\rho_0 c$, of the gauge and sample. $Z_Q = 1.52$ g cm$^{-2}$ $\mu$sec$^{-1}$, and $Z_L = 3.4$ g cm$^{-2}$ $\mu$sec$^{-1}$.

[c] Polymethyl methacrylate.

The authors would like to acknowledge review of the manuscript by W. B. Benedick and J. E. Kennedy and the assistance of G. A. Carlson and T. M. Kerley in the pulsed electron beam experiment.

*Work supported by the U. S. Atomic Energy Commission.

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